TECHNOLOGY STATUS ASSESSMENT FOR DEVELOPMENT OF NONLINEAR HARMONIC SENSORS FOR DETECTION OF MECHANICAL DAMAGE

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INTRODUCTION

The objective of the project is to design and fabricate a nonlinear harmonic (NLH) sensor system for use in detecting mechanical damage in transmission pipelines when deployed on a pipeline inspection pig. Mechanical damage refers to dents and/or gouges caused by impingement on the outside of the pipe, e.g.,. from a backhoe tooth striking the pipe during digging operations. Characterization of mechanical damage to determine potential for pipeline failure requires that stresses and/or plastic deformation be determined; it is not sufficient to measure only the geometry of the defect.

The purposes of this technology status assessment were to identify related work that could be of help to the project and to determine if patents have been awarded for this application. Southwest Research Institute™ (SwRI™) has performed a significant amount of work with NLH, much of it directed at mechanical damage detection and characterization. The technology survey includes relevant information from this work, as well as results from computerized literature searches and knowledge of SwRI staff to identify related work performed by others. Results of the survey and assessment are summarized in Table 1.

CURRENTLY USED AND POTENTIAL MECHANICAL DAMAGE DETECTION METHODS

Geometry Pigs [1]

Geometry pigs (also known as "caliper pigs") are one of a class of in-line inspection tools referred to as "configuration pigs." Configuration pigs are used to measure the shape and size of the pipeline and its position in the right-of-way. In this class, besides geometry pigs, there are also slope-deformation pigs, curvature pigs and mapping pigs.

The earliest geometry pigs produced only one channel of data related to the minimum diameter of the pipeline as a function of axial position. Later refinements included the addition of maximum diameter data. This made it possible to differentiate between denting and ovality since denting only reduces the diameter while ovality reduces diameter on one axis and increases it in the orthogonal axis. Today's geometry pigs use multiple sensing axes together with multichannel recording to collect data that record the pipe radius at many angular positions around the circumference. With these tools, not only can a dent be measured and discriminated from ovality, but it can also be located in an o'clock position. This is important since a dent on the bottom of

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the pipe is most likely due to rock impingement, and a dent on the top of the pipe has a greater chance of being third-party damage.

The geometry pig has been the mainstay of the industry's tools for detecting mechanical damage. Modern geometry surveys can reveal even small dents and fairly accurately measure their extent. Unfortunately, dent depth is not the only mechanical damage parameter that is significant in defect severity. Some dents are smooth and very unlikely to lead to failure, whereas others have gouges in them, leading them to potential failure due to crack initiation and growth. Furthermore, some dents with gouges can be rerounded by hydrostatic testing or pipeline operating pressure, rendering them undetectable by geometry pigs. Therefore, there is a need for a technique such as NLH, which can respond to the defect stress pattern even though the defect has no internal protrusion.

Magnetic Flux Leakage

The magnetic flux leakage (MFL) method is routinely used on inspection pigs to detect pipeline wall-loss defects caused primarily by corrosion [1]. This approach responds to the change in geometry associated with a defect. It is also sensitive to localized changes in magnetic properties of the steel such as those caused by stress and plastic deformation; however, this is a very small effect compared to the changes caused by geometry. MFL has been shown to have some sensitivity to mechanical damage [2,3]. In order for this method to provide information related to stress and plastic deformation, additional steps must be taken beyond those currently used for corrosion detection. Normally, MFL data are taken with a strong magnetic field that makes the technique relatively insensitive to material property changes such as those caused by stress. To detect stress-related changes, additional data must also be taken with a much weaker magnetic field, and then the strong and weak field data are subtracted to reduce the mechanical damage geometry response and leave primarily the stress response. To implement this technique in a pig, an additional set of magnetizers and sensor probes is needed for the weak field measurements.

NLH BACKGROUND

Because of the magnetoelastic effect [4], the magnetic properties of a ferromagnetic material (such as pipeline steel) are influenced by stress and plastic deformation. Therefore, by sensing the magnetic properties of a material, the stress or plastic deformation associated with mechanical damage in a pipeline can be determined. An attractive approach for sensing the magnetic properties for this purpose is the nonlinear harmonics (NLH) method [5,6]. The instrumentation and probes are compatible with pigging requirements, and data can be acquired at pig inspection speeds (1 to 4 m/sec).

NLH measurements are made by applying a sinusoidal magnetic field to the pipe wall. Because of the magnetic hysteresis and nonlinear permeability, the application of a sinusoidal magnetic field (H) to ferromagnetic material results in the distortion of the magnetic induction (B) waveform. The resulting magnetic induction waveform undergoes severe distortion. This distorted waveform contains odd-numbered harmonic frequencies of the applied magnetic field. Mechanical stresses and plastic deformation greatly influence the magnetic hysteresis and permeability of the material [4] and thus influence the harmonics produced. With the NLH method, the third harmonic frequency is detected and its amplitude related to the state of stress and/or plastic deformation. For uniaxial elastic stresses, tension causes an increase in the NLH signal and compression causes a decrease.

LITERATURE SEARCH

Literature searches were performed using the following computerized databases: COMPENDEX (Engineering Index), INSPEC (Database for Physics, Electronics, and Computing), NTIS (Government Reports and Announcements), and ENTEC (German Energy Database). Information was also obtained from the knowledge and contacts of SwRI and Tuboscope personnel. Three different search strategies were used. The first was directed at finding techniques based on harmonics to measure stress, the second was harmonics to measure plastic deformation, and the third was general methods of detecting mechanical damage in pipelines.

RELATED NLH WORK

The literature search results revealed that others have applied NLH to measurement of stress, but the only work for application to mechanical damage was performed by SwRI. An early project [7], although not directly involving NLH, showed that stress and plastic deformation have significant influence on the magnetic properties of typical pipeline steels. This provided good indication that NLH would respond to these influences in pipeline steels because it is highly sensitive to magnetic properties.

In laboratory studies, NLH has been investigated for application to mechanical damage in pipelines [3,8,9]. NLH data have been taken from dents and gouges introduced into laboratory samples by scanning an NLH probe on the inside surface of the pipe [3]. This work showed that the defects could be readily detected, including a gouge that produced no visible deformation on the inside surface. This is important because it shows the potential to detect stresses from a defect that has “rerounded” from internal pressure. Although the largest effect on the NLH signal was obtained in the direct vicinity of the defect, the stress field from the defects could often be detected from a lateral distance of several defect diameters.

The depth of penetration of NLH is determined by the electromagnetic skin depth (inversely proportional to the square root of the product of frequency, magnetic permeability, and electrical conductivity of the sample). Attempts were made to operate at excitation frequencies low enough to penetrate through the thickness of the pipe wall, but NLH signals were small at these frequencies and the response would be significantly affected by the movement of the probe at pig inspection speeds. It was determined that practical measurements would require NLH operation at excitation frequencies of about 10 kHz, which would provide measurements at shallow depths on the inside surface of the pipe; thus, stresses on the outside of the pipe would have to be inferred from their influence on the inside surface. This work also showed that the NLH signal is affected by liftoff variations (changes in the spacing between probe and pipe surface) and that this effect was reduced by operation at 10-kHz excitation.

Work is currently under way to better define the NLH response to stress and plastic deformation around defects [9] and to determine if the defect severity (likelihood of pipe failure) can be ranked by NLH. This work is not complete, but several important aspects of NLH relative to use in pipelines have been determined. This project involved measurements made while scanning the NLH probe in pipe specimens subjected to typical line pressures and showed that operation of probes at these pressures is feasible. It was shown that probe liftoff variations occur around defects because the flat surface of the probe cannot track the curvature of the defect precisely. Initial results show that corrections for liftoff can be accomplished by measuring the phase of the NLH signal and using it to compensate the signal amplitude. Data have been acquired from 18 different defects, and several defects were subjected to burst testing to obtain information about defect severity. These data will ultimately be correlated with the NLH response to determine relationships between NLH signals and potential for failure. In addition, finite element stress calculations are being performed for the defects. Initial results indicate that calculated patterns of stress distributions around the defects generally correspond to the NLH signal patterns, thus showing potential for obtaining stress information. When this work is completed, results will be applied to the current project.

PATENTS

SwRI holds a patent [10] for application of the NLH method to detection of mechanical damage in pipelines. Literature searches of patent databases revealed no other patents for mechanical damage detection methods for pipelines.

CONCLUSIONS

Based on previous work, the approach to be taken in this project to detect mechanical damage using NLH sensors appears feasible and does not appear to have been previously attempted other than at SwRI. Previous work has shown that NLH can detect the stress field around mechanical damage defects, often from a considerable distance from the deformed area. Work is currently under way to relate the NLH response to defect severity, but this work has not been completed. No other related patents were found other than the SwRI patent on NLH.

TABLE 1. PIPELINE MECHANICAL DAMAGE DETECTION METHODS

Method	Principle	Implementation Requirements	Measures Defect Profile on Pipe ID	Detects Re-Rounded Defects	Detects Gouges Without Dent	Detects Stresses from Defect	Potential for Determining Defect Severity	Response Adversely Affected by Defect Geometry
Geometry Pig	Measures defect profile using contact "fingers" or non-contacting sensors	Array of "fingers" or non-contacting sensors such as acoustic or eddy current	Yes	No	No	No	No	Measures geometry
Magnetic Flux Leakage	Measures disturbance of applied constant magnetic field caused by defect and stress	Separate large magnetizers supplying high and low magnetic fields and array of Hall-effect sensors. High and low field data subtracted to reduce defect geometry effect. Magnetizers and sensors in both axial and circumferential directions needed to detect defects in all orientations	Yes	Uncertain	Yes	Yes, but small effect and must separate from geometry signal	Yes	Yes
Nonlinear Harmonics	Stresses change amplitude of odd-numbered harmonic frequencies of applied alternating magnetic field	Array of small probes, each containing magnetic circuit and sensor. Requires only one probe orientation, but both axial and circumferential probes can be used for more detailed stress information.	No	Yes	Yes	Yes	Yes	Minor effect

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